ESTCP
Cost and Performance Report

(ER-201213)

Flexible Reactive Berm (FRBerm) for Removal of Heavy Metals from Runoff Water

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14. ABSTRACT
Small arms firing ranges (SAFRs) located on Department of Defense (DoD) facilities are, in many cases, constructed next to wetland areas, including ponds, lakes, and streams. These wetlands, which may be seasonal, intermittent, freshwater, brackish, or estuarine, represent a potential point of regulatory interest as they are at risk of heavy metal contamination in the runoff water from the adjacent active ranges. The objective of this project is to demonstrate a relatively low-cost, passive, in situ treatment technology for exclusion of toxic metals in runoff water that can meet the needs of the variable terrain and salinity requirements.

15. SUBJECT TERMS
Small arms firing ranges (SAFRs), situ treatment technology, heavy metal contamination, runoff, variable terrain requirements, reactive filter barrier.

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ACRONYMS AND ABBREVIATIONS

AMMTIAC	Advanced Materials, Manufacturing and Testing Information Analysis Center
ARA	Applied Research Associates
BMP	Best Management Practice
CL	Sandy Clay
COTS	Commercial, Off-the-Shelf
CWA	Clean Water Act
DDI S&S	Distilled, Deionized Water Suspend & Settle
DOD	Department of Defense
DPW	Department of Public Works
EL	Environmental Laboratory
EQI	Environmental Quality and Installations
ERDC	Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FR	Final Report
FRBerm	Flexible Reactive Berm
FRTR	Federal Remediation Technology Roundtable
GSL	Geotechnical and Structures Laboratory
HWRC	Hazardous Waste Research Center
ITRC	Interstate Technology Regulatory Commission
K_d	Partition Coefficient
LCCA	Life Cycle Cost Assessment
LEL	Lowest Effect Level
NPDES	National Pollutant Discharge Elimination System
NTU	Nephelometric Turbidity Unit
SAFR	Small Arms Firing Range
SDWA	Safe Drinking Water Act
SEL	Severe Effect Level
TCLP	Toxicity Characteristic Leaching Procedure
TOC	Total Organic Carbon
TRAPPS™	Time Release Amendment Phosphate System™
TS	Treatability Study

TSS	Total Suspended Solids
USAEC	United States Army Environmental Command
USEPA	United States Environmental Protection Agency

<u>Metals</u>

Antimony	Sb
Cadmium	Cd
Chromium	Cr
Copper	Cu
Iron	Fe
Lead	Pb
Magnesium	Mg
Manganese	Mn
Nickel	Ni
Uranium	U
Zinc	Zn

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The work in this report was performed at the U.S. Army Engineer Research and Development Center (ERDC), Vicksburg and Kinder Range, Fort Leavenworth, KS. Funding was provided by the Environmental Security Technology Certification Program (ESTCP) and the U.S. Army Environmental Command (USAEC). The project is designated as ESTCP Project ER-201213: A Flexible Permeable Reactive Barrier for Protection of Wetland Sediments from Heavy Metals in Runoff Water. On-site project work was performed by Advanced Materials, Manufacturing and Testing Information Analysis Center (AMMTIAC), operated by Alion Science and Technology, under Contract FA4600-06-D-0003, Delivery Order #0066.

This report was prepared by Steven L. Larson and W. Andy Martin of the ERDC Environmental Laboratory (EL), Mark Dortch of Los Alamos Technical Associates, J.J. Romano of Alion, Inc., Jeff Sylva of GSI, Inc. and Catherine C. Nestler of Applied Research Associates, Inc. (ARA). The contractor installation and demobilization team consisted of Alion, the Filtrexx advisor, and GSI Pacific personnel. Robert Kirgan of USAEC oversaw administration of the sub-contract to Alion and GSI. Chemical analysis of the soil and sediment samples was performed by ERDC-EL-Environmental Chemistry.

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

This project addresses the contamination of surface receiving waters by munitions residue-contaminated runoff water and sediment from training ranges. Small arms firing ranges (SAFRs) located on Department of Defense (DOD) facilities are, in many cases, constructed next to wetland areas, including ponds, lakes, and streams. Access to wetland areas (especially forested wetlands) is typically limited due to a lack of roads. Standard environmental remedial options and monitoring techniques are expensive to implement due to the nature of the terrain and seasonal changes in water flow and salinity. Thus, there is a need for a relatively low-cost, passive, in situ treatment technology for exclusion of toxic metals and sediment in runoff water that can meet the needs of the variable terrain requirements.

Two factors influence the amount of lead transported off-site by surface water runoff: the mass of lead fragments left on the range and the velocity of the runoff water. The velocity of the water can successfully be controlled at outdoor ranges by using vegetative, organic, removable, and/or permanent ground covers, and by implementing engineered controls which slow down surface water runoff and prevent or minimize the chances of lead migrating off-site (United States Environmental Protection Agency [USEPA] 2005).

Current methods for treating heavy metals in runoff water include precipitation and flocculation, treatment with ion exchange resins, and phytoremediation. The costs of these technologies are driven by size and complexity of the site being treated, pre-treatment requirements, and post-treatment/disposal of contaminated treatment waste. The performance objectives of this demonstration were to validate the use of the filter sock to remove sediment bound metals as well as soluble metals (i.e., lead) from SAFR runoff water in a manner that was less expensive, time-consuming and labor-intensive to training range management. A second objective was to validate the sediment transport model developed by the Engineer Research and Development Center Environmental Laboratory (ERDC-EL) for use on SAFRs. Both of these objectives were successfully met.

TECHNOLOGY DESCRIPTION

This technology is a reactive filter barrier to trap both metal-contaminated sediment and soluble metals from stormwater runoff. It combines the proven use of geotextile fabric woven into a tubular shape (a “sock”) filled with sand and with the addition of amendments to adsorb both suspended sediments from surface water as well as cationic (such as lead [Pb], zinc [Zn], and copper [Cu]) and anionic (such as antimony [Sb]) metals, metalloids, and metals bound to the suspended solids. The filter sock is National Pollutant Discharge Elimination System (NPDES)-approved for use on construction sites in order to control transport of sediment in surface water.

The sand filter sock performance model (Dortch 2013, Larson et al. 2016) was applied to the North Kinder Range at Fort Leavenworth, KS. The model was used to assess sand filter sock performance for a design storm. Performance measurements consisted of required filter sock diameter and length, and estimate of filter sock life due to sediment clogging. Other measurements included removal of suspended solids, mass of sediment trapped, and change in the filter sock removal coefficient and saturated hydraulic conductivity for the design storm

DEMONSTRATION RESULTS

Bench-scale treatability testing established the Partition Coefficient (K_d) and leachability of the sand/amendment combinations (Larson et al., 2016). Time Release Amendment Phosphate System™ (TRAPPS™) was selected as the amendment for the reactive filter socks.

The demonstration was performed on the North and Center Kinder Ranges at Fort Leavenworth, KS. The North Range was set out according to the runoff water model; the Center Range was an *ad hoc* design. On both ranges, filter socks filled with sand and metal sorption amendment were placed in the flow path of heavy metal-contaminated runoff water. Sediment that pooled upflow of each reactive barrier and the contents of each reactive barrier on both ranges were sampled prior to project demobilization. The solids were analyzed for heavy metals and Toxicity Characteristic Leaching Procedure (TCLP). On both ranges, the Pb concentration in sediment deposited upstream of the barriers was much higher than that in the barriers themselves. Reactive barrier filler material passed TCLP for Pb which would allow disposal of the barriers in a non-hazardous waste site or possible re-use on-site.

IMPLEMENTATION ISSUES

Implementation issues associated with this technology are the site soil erodibility, the concentration of sediment carried by the surface water runoff, and the annual volume of storm runoff water. Runoff water with high sediment concentrations will require more frequent change-outs of the foremost reactive barrier as the barrier will clog more rapidly. This will increase the cost of maintaining the technology. In drought years, the life of the barriers would be extended. In rainy years, or tropical climates with high rainfall, and high sediment transport, the lifetime of the barrier could be reduced.

In summary,

- Reactive filter barriers were successful at removing sediment from runoff water when placed according to the stormwater model developed by ERDC-EL.
- Reactive filter barriers were successful at removing Pb from runoff water when placed according to the stormwater model developed by ERDC-EL.
- Coarse sand would provide greater flow through the reactive filter barriers and decrease sediment deposits upstream of the barriers.
- Heavy metal adsorption amendments in the reactive filter barrier allow the barrier contents to pass the TCLP which reduces hazardous waste disposal costs.

The technology has been transferred to Range 9, Fort Jackson, SC. Reactive barriers were placed on range according to the runoff water model on 26 April 2016. A contractor, Alion Inc., was responsible for the installation. U.S. Army Environmental Command (AEC) will receive a copy of all reports concerning this technology. A commercial vendor is also involved in the technology transfer, as Alion used the metal binding amendment supplied by Filtrexx, Inc. in the reactive barriers.

1.0 INTRODUCTION

1.1 BACKGROUND

This project addresses the contamination of surface receiving waters by munitions residue-contaminated runoff water and sediment from training ranges. Small arms firing ranges (SAFRs) located on Department of Defense (DOD) facilities are, in many cases, constructed next to wetland areas, including ponds, lakes, rivers, and streams. These wetlands represent a potential point of regulatory interest as they are at risk from heavy metal contamination in the runoff water from the adjacent active ranges. Access to wetland areas (especially forested wetlands) is typically limited due to a lack of roads. Standard environmental remedial options and monitoring techniques are expensive to implement due to the nature of the terrain and seasonal changes in water flow. Thus, there is a need for a relatively low-cost, passive, in situ treatment technology for exclusion of toxic metals in runoff water that can meet the needs of the variable terrain and rainfall.

This potential treatment is based on the proven use of a geotextile fabric woven into a tubular shape ("filter sock") and filled with sand (Figure 1). The filter sock is National Pollutant Discharge Elimination System (NPDES)-approved for use on construction sites in order to control transport of sediment in surface water. In a SAFR berm, metals occur in the form of discrete particles (intact munitions or fragments), as well as metal salts (weathering products) and dissolved metal or metallic complexes adsorbed to the soil matrix. When these soils are eroded, the particulate metals that are adsorbed to soils also move with the runoff water (Davis and McCuen 2005, Tardy et al. 2003).

Figure 1. Illustration of a Sediment Control Filter Sock

Metal removal can be enhanced with the addition of amendments to the sand that will adsorb both cationic (such as lead [Pb], zinc [Zn], and copper [Cu]), and anionic (such as antimony [Sb]) metals/metalloids, and metals bound to suspended solids. The chemical amendment employed was a proprietary commercial mixture of Time Release Amendment Phosphate System™ (TRAPPS™) (Slater UK, Limited) mixed with clean sand. TRAPPS™ is an apatite formulation [$Ca_{10-x}Na_x(PO_4)_{6-x}(CO_3)_x(OH)_2$ with $x < 1$], with relatively insoluble minerals (e.g., phosphate, iron and manganese-based) tailored to stabilize specific contaminants of concern (i.e., Pb, Sb) (Larson et al., 2007b, Wynter et al. 2012).

Dortch (2013) developed a mathematical model to predict the performance and Total Suspended Solids (TSS) removal characteristics of sand filter socks such as the flexible reactive barrier. The model included the effects of TSS clogging the socks over time. The intended use of the model is for site-specific design of the filters prior to construction and implementation. This model was used to provide design information and predict filter performance for surface runoff water on the field demonstration site.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives of the field demonstration were to:

- Validate application of the reactive filter barrier technology at field scale, and
- Validate the sediment transport model developed by the Engineer Research and Development Center Environmental Laboratory (ERDC-EL).

Both of these objectives were successful.

1.3 REGULATORY DRIVERS

Research has shown that the majority of heavy metals leaving small arms ranges is associated with the suspended solids in the runoff water (Tardy et al. 2003). This scenario is directly impacted by the U.S. Clean Water Act (CWA) of 1972. Lead in water is regulated under both the CWA and the Safe Drinking Water Act (SDWA). Individual states and tribes may adopt water quality standards that are more stringent than the Federal regulations but not less protective. The final regulations for lead were adopted by the United States Environmental Protection Agency (USEPA) in 1991.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

The flexible reactive barriers are based on the known, well-tested sediment removal filter socks used in the construction industry with an additional metal-sorbing amendment added to the sand. The results of treatability testing are presented in Larson et al. (2016). The sand filter sock performance model (Dortch 2013) was applied to the North Kinder Range at Fort Leavenworth, KS (Figure 2). The model was used to assess sand filter sock performance for a design storm. Performance measurements consisted of required filter sock diameter and length to avoid or decrease water over-topping for the design storm and estimate of filter sock life due to sediment clogging. Other measurements included mass of TSS removal and change in the filter sock removal coefficient and saturated hydraulic conductivity (Larson et al. 2016). Filter socks were arranged in series and allowed for over-topping in heavy rainfall conditions. The demonstration on the Center Kinder Range did not employ the model for determining number and placement of the reactive filter barriers.

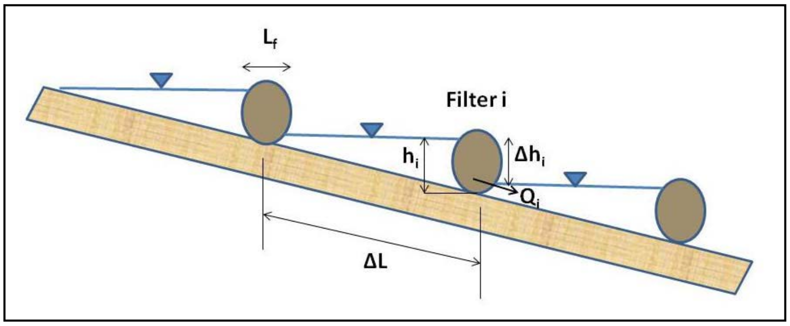

Figure 2. Conceptual Design of the Flexible Reactive Filter Barriers to Remove Soluble and Sediment Bound Metal(loids) in Stormwater Runoff.

The reactive barrier filter socks in place on the North Kinder Range is shown in Figure 3. This technology is expected to be applied on SAFRs, military or civilian, where runoff water crosses the range and carries contaminated sediment and soluble metals to a surface water receiving point.

Figure 3. Positioning of the Reactive Filter Barriers in the Flowpath of Range Runoff Water on North Kinder Range, Fort Leavenworth, KS.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Two factors influence the amount of lead transported off-site by surface water runoff: the mass of lead fragments left on the range and the velocity of the runoff water. The velocity of the water can successfully be controlled at outdoor ranges by: (1) using vegetative, organic, removable, and/or permanent ground covers; and (2) implementing engineered controls which slow down surface water runoff and prevent or minimize the chances of lead migrating off-site (USEPA 2005). Dams and dikes installed perpendicular to the water flow, and ground contouring to divert the flow, are both recommended engineered control devices to slow runoff water. Construction of detention ponds and contaminant traps are other engineered control devices (USEPA 2005).

One of the current methods for simply containing the sediment in runoff water is a silt fence. These are temporary devices, used primarily on construction sites. The fence is porous fabric, held up by wooden or metal stakes (Figure 4). The silt fence is designed to protect quality of nearby receiving waters from sediment carried by stormwater runoff. Runoff water moves through the fence material. A single 100-foot run of fence can hold back 50 tons of sediment. The advantages of silt fences are their low cost and simple design. However, they have shown limited effectiveness for sediment control due to poor installation practices, improper placement and/or inadequate maintenance (USEPA 2012). Training in their placement and enhanced installation methods have reduced some of these challenges (USEPA 2012). However, the silt fence was never designed to remove heavy metals or other contaminants from the sediment and runoff water.

Figure 4. Example of the Use of a Silt Fence as a Best Management Practice for Sediment Control in Runoff Water from a Construction Site.

Current methods for treating heavy metals in runoff water collected in retention ponds or other containment structures include precipitation and flocculation, treatment with ion exchange resins, and phytoremediation (http://www.frtr.gov, accessed 11 November 2015). The costs of these technologies are driven by size and complexity of the site being treated, pre-treatment requirements, and post-treatment/disposal of contaminated treatment waste. For example, removal of heavy metals by precipitation/flocculation requires collection of the stormwater to be treated, disposal of the contaminated sludge, and a system to return the treated water to the surface water. The

precipitation/flocculation treatment is reported to cost from $17.00 to $41.00 per 1,000 gallons of water. This cost does not include either the pre- or post-treatment. Sludge disposal could add an additional $0.50 per 1,000 gallons.

The flexible reactive berm was designed to be a low-cost alternative technology between simple sediment removal devices and complicated and expensive metal treatment technologies. The reactive barrier:

- retains the flexibility and sediment removing function of the silt fence, and
- adds the ability to remove metals directly from runoff water and sediment fines.

The advantages of the flexible reactive barriers are the relatively low cost and its superior performance across rough terrain and in environments difficult to access. The flexible reactive berm combines the advantages of reducing the velocity of the runoff water through engineered controls with heavy metal treatment by removal of particulate metals and adsorption of dissolved metals.

The disadvantage of the flexible reactive berm is on ranges with heavy sediment transport in the runoff water. This leads to early clogging of the filters and a reduced filter lifetime. These disadvantages can be overcome by employing the runoff water sediment control model developed by ERDC-EL.

Alternative technologies include other commercial metal-sorbing amendments that could be used on their own or mixed with sand in the reactive filter barriers for improved sediment removal. These include MetalLoxx® by Filtrexx.

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3.0 PERFORMANCE OBJECTIVES

Performance objectives and assessment of demonstration results are presented in Table 1.

Table 1. Performance Objectives

Performance Objective	Data Requirements	Success Criteria
Quantitative Performance Objectives		
Reduce concentration of heavy metals (Pb, Cu, Zn, Sb) in runoff water from the SAFR.	Pre- and post-treatment metal concentrations in runoff water	Below Federal and/or State regulatory limits, where established; Pb=15 ppb, Sb=6 ppb, Cu=1.3 ppm, Zn=not stated.
Reduce concentration of TSS in runoff water	Pre- and post-treatment TSS concentrations in runoff water	Turbidity shall not exceed 10 NTU over background turbidity when the background turbidity is 50 NTU or less
Technology amendments pass TCLP metal regulatory requirements (Pb, Cu, Zn, Sb) for disposal in a non-hazardous waste site	TCLP of saturated amendments	Technology amendments pass TCLP for metals (Pb, Cu, Zn, Sb), if a regulatory level is available
Maintain runoff water pH levels at background levels	pH measurements of water samples collected on site and in the runoff pathways from the site	Runoff water pH = background levels
Maintain runoff water pH levels	pH measurements of water samples collected on site and in the runoff pathways from the site	Soil pH = background levels
Maintain nutrient and TOC concentrations in runoff water at levels to prevent eutrophication of surface water	Pre- and post-treatment nutrient and TOC concentrations in runoff and receiving water	Below Federal and/or State regulatory limits for nutrients and TOC in runoff water; nitrate=10 ppm, TOC=0.05 ppm
Determine length of use of the amendment technology based on local soils, metal concentrations and precipitation	Pre- and post-treatment metal concentrations in runoff water to establish breakthrough times, range use, local precipitation amounts	Determine treatment technology replacement time
Qualitative Performance Objectives		
Ease of use	Feedback from field technicians on time required for treatment placement, frequency of replacement and range downtime	Technology placement requires no or minimal downtime of the range
Evaluate range management costs	Technology placement method, frequency, and range downtime	LCCA model to develop annual cost to maintain the demonstration range and other ranges

LCCA Life Cycle Cost Assessment
NTU Nephelometric Turbidity Unit
TCLP Toxicity Characteristic Leaching Procedure
TOC Total Organic Carbon

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4.0 SITE DESCRIPTION

4.1 SITE LOCATION

Fort Leavenworth is located in Leavenworth County, Kansas, immediately north of the city of Leavenworth in the upper northeast portion of the state (Figure 5). It is bordered on the east by the Missouri River and the state of Missouri. The fort currently occupies 5,600 acres.

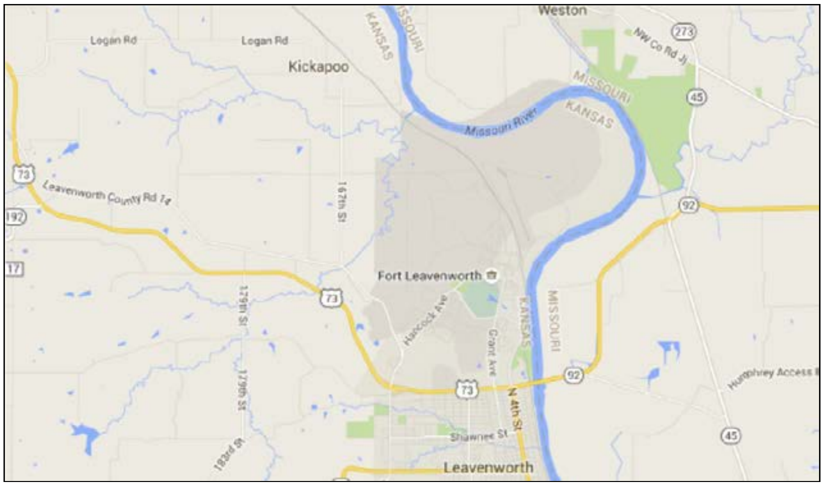

Figure 5. Map Showing the Relationship of Fort Leavenworth, KS to the Missouri River

The field demonstration was conducted on the Kinder Range (Figure 6); the North and Center ranges. The firing lines are located adjacent to the road seen in the upper right corner of the photograph. The hillside is used as the impact berm. A satellite view of North Range is shown in Figure 7 with details of the impact area in Figure 8. The Kinder Center Range is shown in Figure 9 and detailed in Figure 10.

Figure 6. Fort Leavenworth Kinder Range, North and Center Small Arms Firing Ranges, Site of the Field Demonstration.

Figure 7. Satellite View of the North Kinder Range, Fort Leavenworth, KS.

Firing lines are adjacent to the road. The impact area is the hillside under the trees.

Figure 8. North Kinder Range, Fort Leavenworth, KS Looking Towards the Impact Area on the Hillside.

Figure 9. Satellite View of Center Kinder Range, Fort Leavenworth, KS.

Figure 10. Left. View from the Firing Line towards the Hillside Impact Area. Right. Detail View of the Impact Area Highlighting the Extended Bullet Pockets.

4.2 SITE GEOLOGY/HYDROGEOLOGY

As shown in the figures above, the SAFR berms are the natural earthen slope. Behind this impact berm, there is a wooded area. The trees cover a large, raised plateau with a steep slope down to the range areas. Repeated firing into this slope has resulted in long, deep bullet pockets, which are visible from the tree line toward the firing lines. The soils of Leavenworth County, KS consist predominantly of silty clay and silty clay loam. Soil from the Kinder Range area has been classified as a gray, Sandy Clay (CL). The soil particle size distribution is: 9.9% gravel, 22.6% sand, and 67.5% fines. Of the fines, 38.7% were determined to be silt-sized particles and the other 28.8% consisted of clays.

During the field demonstration, 1 June 2015 to 16 October 2015, there was >15.27 in of rain, with a monthly average of 3.82 in.

4.3 CONTAMINANT DISTRIBUTION

Metal contamination is localized to the bullet pockets and the bullet pocket gullies. Runoff water flows through the bullet pockets transporting soluble munitions metals and metal(loids) sorbed to sediment.

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5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The technology components of this study were the reactive filter sock barrier and a range runoff water model developed by Dr. Mark Dortch and Dr. Billy Johnson (ERDC-EL) through funding leveraged with the Environmental Quality and Installation (EQI) 6.2/6.3 Green Range Program (Johnson and Dortch 2014). Baseline values for Pb concentration were the concentrations in the sediment upstream of the first reactive barrier. The model was used to optimize placement of the reactive filter barriers in the flowpath of runoff water from the hillside berms.

5.2 BASELINE CHARACTERIZATION

Soil characterization was performed for the Kinder Range soils by the Geotechnical and Structures Laboratory (GSL) of ERDC. The soil was classified as a gray, Sandy Clay (CL). The soil particles size distribution is: 9.9% gravel, 22.6% sand, and 67.5% fines. Of the fines, 38.7% were determined to be silt-sized particles and the other 28.8% consisted of clays (Larson et al. 2016).

5.3 TREATABILITY STUDY RESULTS

The results of treatability studies have been detailed in Larson et al. (2016). In summary, as a result of K_d and leach testing evaluation of potential amendments, a combination of sand and a commercial amendment, TRAPPS™, was selected for the reactive filter socks. The amendment was added to the sand at a 5% loading rate. The filter socks were a commercial geotextile supplied by Filtrexx® International.

Grading of the berm on the north side of the North Range was required by Fort Leavenworth range management. These range modifications were added to the runoff water model which recommended a series of three reactive barriers for the North Kinder Range.

5.4 FIELD TESTING

The Gantt chart (Table 2) shows the schedule for each phase of the field test and how the operational phases were related. The key decision point for this demonstration was the occurrence of rain, both in number of events and in total rainfall. A major rain event occurred two days after system startup and provided immediate feedback on the sturdiness and effectiveness of the flexible reactive berms placed in the flowpath of the runoff water. Following additional rain events in July and August, a date was selected, working with Fort Leavenworth DPW, for system demobilization. During the field demonstration, 1 June 2015 to 16 October 2015, there was >15.27 in of rain, with a monthly average of 3.82 in.

Table 2. Gantt Chart for Field Demonstration of the Flexible Reactive Berms Applied at Kinder Range, Fort Leavenworth, KS.

Task	June	July	Aug	Sept	Oct	Nov	Dec
System startup – completed 2 June 2015							
System operation							
System demobilization – completed 16 October							
Sample analysis							
Reporting							

5.5 SAMPLING METHODS

No samples were collected during the period of the field demonstration of the flexible reactive barriers due to a lack of funding. When the project was complete, but before disassembly of the filter barriers, samples were collected from the sediment that collected in the front of each barrier as well as from the contents of the barriers themselves. Samples were analyzed for heavy metals and TCLP. The reactive berm assembly and sampling plan for the North Kinder Range is shown in Figure 11; that of the Center Kinder Range is shown in Figure 12.

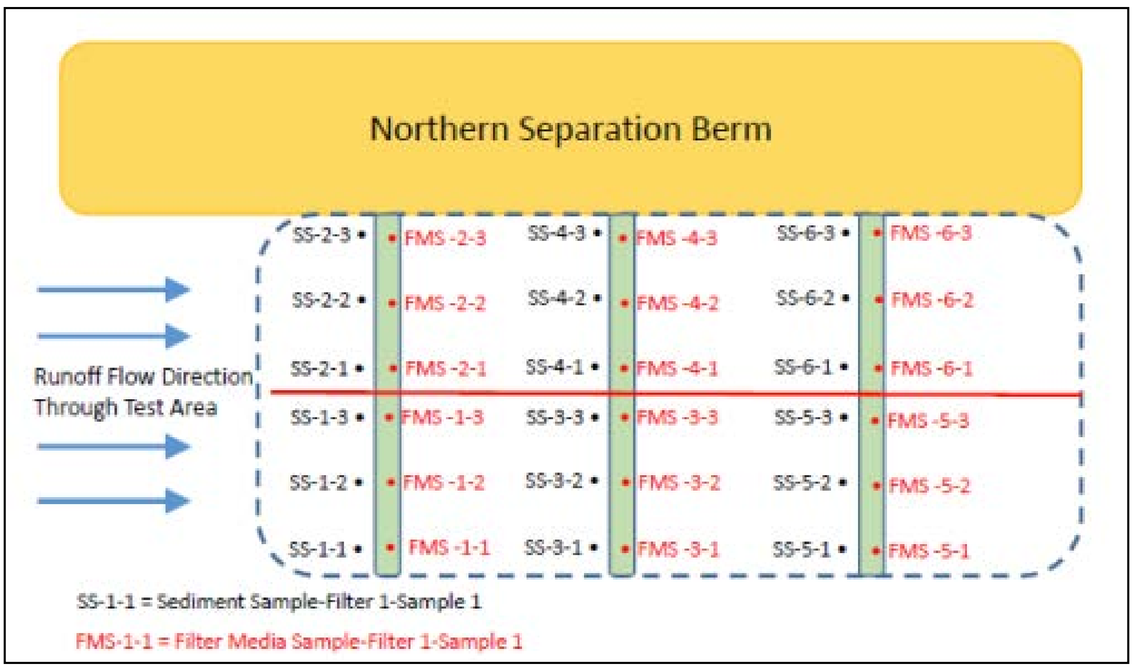

Figure 11. Reactive Barrier Assembly and Sampling Plan for the North Kinder Range, Fort Leavenworth, KS.

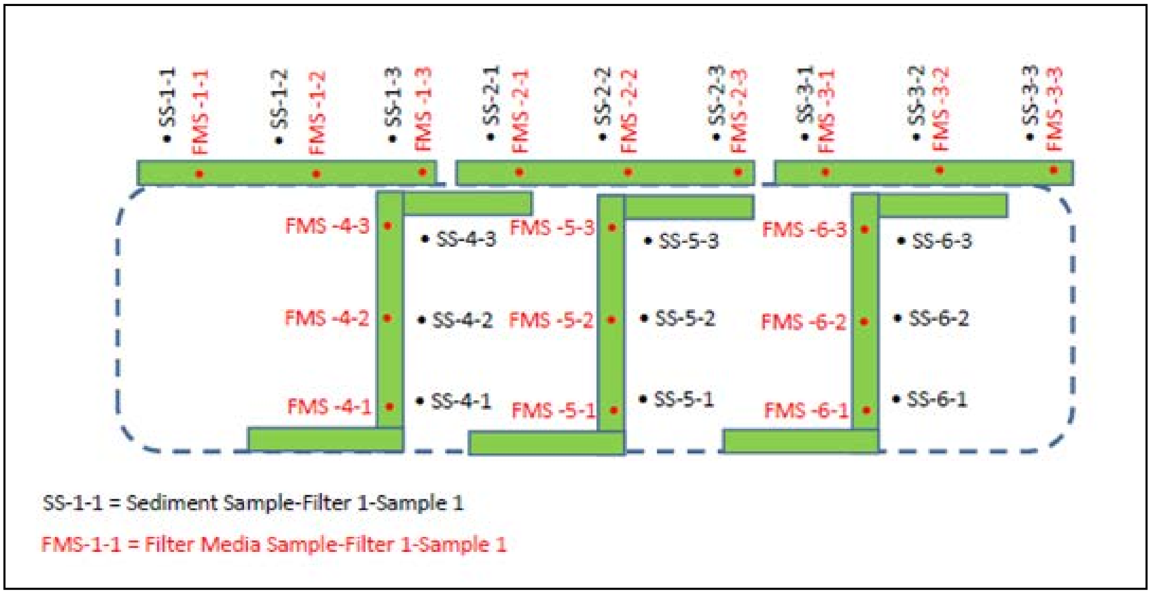

Figure 12. Reactive Barrier Assembly and Sampling Plan for the Center Kinder Range, Fort Leavenworth, KS.

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6.0 SAMPLING RESULTS

6.1 NORTH KINDER RANGE

The average concentration of Pb in the reactive barrier is compared to the average concentration of Pb in the sediment upstream of the barriers (Table 3) for each flowpath of the runoff water. The concentration of lead extractable from within the reactive barrier filters was observed to be much less than that extracted from the sediment deposited in front of each sock.

Table 3. Comparison of Pb Concentration in Reactive Filter Barriers and their Related Upstream Sediment Deposits, North Kinder Range, Fort Leavenworth, KS

Position		Pb concentration (mg/kg)	
		Avg (n=9)	Stdev
North flowpath	Sediment	2,597	2,175
	Reactive barriers	50	76
South flowpath	Sediment	6,283	1,273
	Reactive barriers	86	43

A comparison of the TCLP analysis of the sediment in front of each reactive barrier and within the reactive barriers is shown in Table 4. Lead was the only metal observed over the TCLP regulatory limit. Lead only exceeded the limit in the untreated sediment from the runoff water. The reactive barriers successfully adsorbed the lead on the TRAPPS™ amendments. At the end of the useful life of the barriers the contents could be reused on-site (with management approval) as berm material or disposed of as non-hazardous waste. This option has the potential to decrease range management costs for the installation.

Table 4. Results of TCLP Analysis of Upstream Sediment and Reactive Barriers from the North Kinder Range, Fort Leavenworth, KS. Exceedances are shown in Red.

Metal	TCLP Regulatory Limit (mg/L)	Concentration (mg/L)			
		North Range Sediment		North Range Reactive Barriers	
		North flowpath	South flowpath	North flowpath	South flowpath
Arsenic	5	0.02	0.03	0.02	nd
Barium	100	1.75	1.28	0.38	0.35
Cadmium	1	0.02	nd	nd	nd
Chromium	5	nd	nd	nd	nd
Lead	5	48.70	141.33	0.07	0.02
Selenium	1	0.02	0.02	nd	0.03
nd – non-detect					

6.2 CENTER KINDER RANGE

A study was undertaken using the Center Range reactive barrier (amended) samples to establish whether the Pb was preferentially associated with a particular soil particle size. The samples were separated by wet sieve using a SWECO Vibro-Energy Round Separator with discreet screen sizes. The particle size fractions analyzed were <200 mm, <135 mm, <50 mm, <35 mm, <20 mm, and >20mm. The sieve water was also analyzed for soluble metals. The >20 mm fraction was composed primarily of small rocks. Figure 13 illustrates the concentration of munitions-associated heavy metals (Sb, Cu, Pb, Nickel [Ni], and Zn) in the different soil particle size fractions from the amended sand in the reactive filter barrier. No munitions metals were detected in the soluble fraction; all munitions metals were contained in the reactive filter barriers. Cu, Zn, and Pb were detected primarily in the <200 mm fraction. However, Pb was also observed in the <35 mm and the <20 mm fractions.

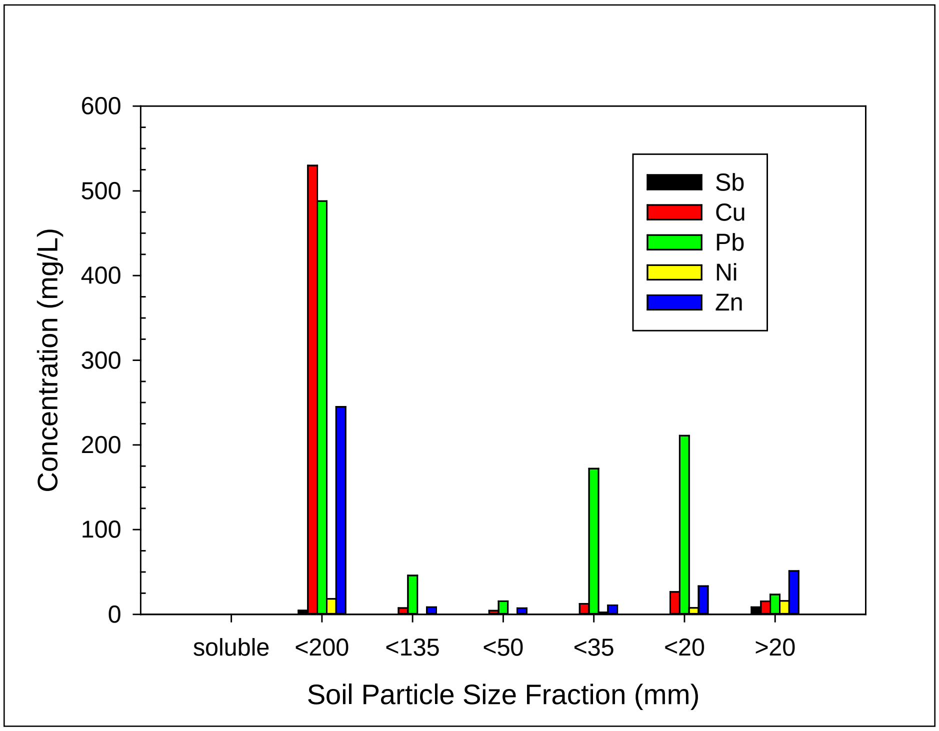

Figure 13. Occurrence and Concentration of Munition-Associated Heavy Metals by Soil Particle Size in Sediment from the Center Kinder Range, Fort Leavenworth, KS.

In Figure 14, the Pb concentrations in each soil size fraction are compared to that of iron (Fe) a non-munition metal that is part of the TRAPPS™ amendment formulation. The Pb concentration closely follows the amendment, as represented by the Fe, except in the >20 mm fraction. The high Fe concentration in this fraction probably reflects the nature of the fraction; primarily small rocks.

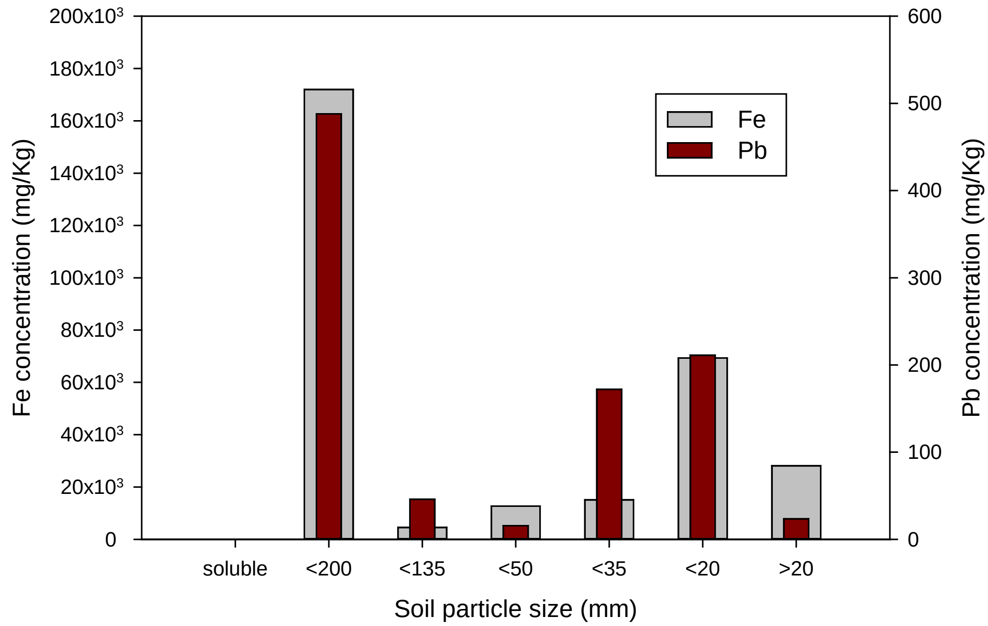

Figure 14. Comparison of Lead (Pb) Concentration to that of Iron (Fe), a Component of the TRAPPS™ Formulation, in the Reactive Barrier Filler Material Used on the Center Kinder Range.

Triplicate samples were taken from sediment that built up in front of each of three reactive barriers behind the trench at the bottom of the hill berm. Samples were also taken from in front of each reactive barrier inside the firing line trench. The in-trench reactive barriers received water that overtopped the hill barriers along the entire length of the trench. The triplicate sample from each reactive barrier were combined, dried, homogenized, and analyzed for heavy metals. The sediment from the reactive barriers on the hill contained an average of 4,373 ± 1,635 mg/kg of Pb. The sediment from the reactive barriers located in the trench contained an average of 7,560 ± 2,469 mg/kg of Pb. Results of a student t-test performed on the data indicate that there is not a statistically significant difference between the two sets of data (P=0.136). This result is probably due to the heavy overtopping that was observed during most rain events (anecdotal from contractor's report). Sediment containing Pb was carried by the untreated storm runoff water into the trench. Therefore, each reactive barrier in the trench functioned more as a primary treatment instead of secondary or tertiary treatment.

The average concentration of Pb in the reactive barrier is compared to the average concentration of Pb in the sediment upstream of the barriers for each flowpath of the runoff water (Table 5).

Table 5. Comparison of Pb Concentration in Reactive Filter Barriers (Hill and Trench) and their Respective Upstream Sediment Deposits.

Position		Pb Concentration (mg/kg)	
		Avg (n=9)	Stdev
Hill berm behind target trench	Sediment	4,373.33	1,635.37
	Reactive barriers	180.47	118.81
In trench	Sediment	7,560.00	2,469.39
	Reactive barriers	168.87	150.34

A comparison of the TCLP analysis of the sediment in front of each reactive barrier and within the reactive barriers is shown in Table 6. Each metal for which there is a TCLP regulatory limit is included in this table. Lead was the only metal observed over the TCLP regulatory limit. Lead only exceeded the limit in the untreated sediment from the runoff water. The reactive barriers successfully adsorbed the Pb on the TRAPPS™ amendments. At the end of the useful life of the barriers the contents could be reused on-site (with management approval) as berm material or disposed of as non-hazardous waste. This option has the potential to decrease range management costs for the installation.

Table 6. Results of TCLP Analysis of Upstream Sediment and Reactive Barriers from the Center Kinder Range, Fort Leavenworth, KS. Exceedances are shown in Red.

Metal	TCLP Regulatory Limit (mg/L)	Concentration (mg/L)			
		Center Range Sediment		Center Range Reactive Barriers	
		Hill	Trench	Hill	Trench
Arsenic	5	0.03	0.04	nd	nd
Barium	100	2.12	1.60	0.36	0.38
Cadmium	1	nd	nd	nd	nd
Chromium	5	nd	nd	nd	nd
Lead	5	145.00	136.00	1.52	4.21
Selenium	1	0.03	0.03	0.02	0.03
nd – non-detect					

6.3 PERFORMANCE ASSESSMENT

A performance assessment of the reactive barrier technology as demonstrated on the North Kinder Range, Fort Leavenworth, KS is provided in Table 7. The modeling, based on the results of Larson et al. 2016, assumed a filter medium of course sand with a median grain size on the order of 1 mm. At the demonstration site, two finer grain sands had been purchased, therefore, they were used in the filter socks for the demonstration. Finer grain size causes less water to flow through the filter with more water ponding before eventual over-topping. When water flows more easily through the filter, there is greater tendency for TSS to be trapped within the filter rather than settling out of the ponded water column upstream of the sock. By moving through the filter, the metals are adsorbed onto the reactive amendment. The sampling results of the North Kinder Range indicate that far more lead (and the TSS onto which lead is adsorbed) was settled upstream of the filters than trapped within the filters.

It is believed that the use of coarser sand within the filters would have resulted in more lead being trapped within the filters and less lead settled upstream of them.

Table 7. Performance Assessment of the Reactive Filter Barrier as Demonstrated on North Kinder Range, Fort Leavenworth KS.

Performance Objective	Data Requirements	Success Criteria	Result
Quantitative Performance Objectives			
Reduce concentration of heavy metals (Pb, Cu, Zn, Sb) in runoff water from the SAFR.	Pre- and post-treatment metal concentrations in runoff water	Below Federal and/or State regulatory limits, where established; Pb=15 ppb, Sb=6 ppb, Cu=1.3 ppm, Zn=not established.	Due to lack of funding runoff waters were not sampled
Reduce concentration of TSS in runoff water.	Pre- and post-treatment TSS concentrations in runoff water	Turbidity shall not exceed 10 NTU over background turbidity when the background turbidity is 50 NTU or less	Due to lack of funding runoff waters were not sampled
Technology amendments pass TCLP metal regulatory requirements (Pb, Cu, Zn, Sb) for disposal in a non-hazardous waste site	TCLP of saturated amendments	Technology amendments pass TCLP for metals (Pb, Cu, Zn, Sb), if a regulatory level is available	All socks with the reactive filter barrier passed the TCLP for Pb and for Cu, Zn, and Sn. Sediment that did not pass through the socks did not pass the TCLP for Pb, Cu, Zn or Sn.
Maintain runoff water pH levels	pH measurements of water samples collected on site and in the runoff pathways from the site	Soil pH = background levels	Due to lack of funding runoff waters were not sampled
Maintain nutrient and TOC concentrations in runoff water at levels to prevent eutrophication of surface water	Pre- and post-treatment nutrient and TOC concentrations in runoff and receiving water	Below Federal and/or State regulatory limits for nutrients and TOC in runoff water; nitrate=10 ppm, TOC=0.05 ppm	Due to lack of funding runoff waters were not sampled
Determine length of use of the amendment technology based on local soils, metal concentrations and precipitation.	Pre- and post-treatment metal concentrations in runoff water to establish breakthrough times, range use, local precipitation amounts	Determine treatment technology replacement time	Runoff waters were not sampled. Longevity assessments were made using the Pb concentration in sediment and reactive barrier material
Qualitative Performance Objectives			
Ease of use	Feedback from field technicians on time required for treatment placement, frequency of replacement and range downtime	Technology placement requires no or minimal downtime of the range	Success
Evaluate range management costs	Technology placement method, frequency, and range downtime	LCCA model to develop annual cost to maintain the demonstration range and other ranges	LCCA model was not developed due to lack of funding. Contractor provided long-term technology implementation plan

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7.0 COST ASSESSMENT

7.1 COST MODEL

A simple cost summary of the flexible, reactive berm (FRBerm) technology is provided in Table 8. The major cost elements include the geotextile and the reactive filler material for each sock. These are site specific costs. Costs are given per linear foot of reactive barrier. Labor to install the reactive socks was not a significant cost but is noted in Table 8. Waste disposal of contaminated reactive socks and sediment accrued by the field demonstration was handled by the EL-Hazardous Waste Research Center (HWRC). Disposal costs to the installation on implementation of this technology was estimated by the field installation contractor and is included in Table 8. As the filler material passed the TCLP test, it could be sent to a non-hazardous waste landfill or reused on-site in, for example, berm construction.

Table 8. Cost Model for Reactive Barrier Filters.

Cost Element	Data Tracked During the Demonstration	Costs	
Treatability study	• Personnel required and associated labor • Materials • Analytical laboratory costs	Lab technician, 80 h Project engineer, 80 h	$32,000 $67,300
		Materials	$23,500
		Analytical laboratory	$5,400
Baseline characterization	• Detailed hydraulic assessment required, costs associated with labor and materials tracked	Field technician, 40 h Project engineer, 15 h	$15,000 $36,700
		Materials	$10,000
Total non-recurring initial costs			**189,900**
Material cost	Unit: $ per foot of reactive barrier Data requirements: • Initial amount of material required based on recommended width and depth of reactive sock • Reapplication rate as stated in surface water model and life cycle analysis	• COTS product costs range from $3.33 to $14.58 per foot of pre-filled reactive filter barrier. Cost varies depending on the type of amendment. • Shipping costs are $2.08 per foot of reactive barrier. • Re-application frequency is detailed in Table 12.	
Installation	Unit: $ per year Data requirements: • Recommended installation method • Mobilization cost • Time required	• Labor $1,000 per year for 2 ranges installation/removal of reactive barriers. • Installation required one, eight hour day for three workers and included site preparation (grading) where deemed necessary by installation DPW. • COTS reactive barriers are delivered with the approved installation stakes, which are included in the cost and shipping charges.	
Waste disposal	• Hazardous waste sediment disposal	$10,000/year, contractor estimate for Pb-contaminated sediment	
Operation and maintenance costs	• No unique requirements	NA	
Long-term monitoring	• Not required	NA	

COTS Commercial, Off-the-Shelf

7.2 COST DRIVERS

The cost drivers for implementation of this technology are the concentration of sediment carried by the surface water runoff and the annual volume of storm runoff water. Runoff water with high sediment concentrations will require more frequent change-outs of the foremost reactive barrier as the barrier will clog more rapidly. This will increase the cost of maintaining the technology. In drought years, the life of the barriers would be extended. In rainy years, or tropical climates with high rainfall, and high sediment transport, the lifetime of the barrier could be reduced.

7.3 COST ANALYSIS

The cost analysis is based on a site the size of a small to medium firing range with soil berm in a temperate region with moderate rainfall. The North Kinder Range has an approximate catchment area of 2,500 m^2, or about 0.6 acres. The ERDC-EL sediment model uses an average annual maximum 24-hour storm, which has a rainfall of about 2.85 inches (USDC 1961). Full parameters are described in Larson et al. (2016).

One of the current methods for simply containing sediment in runoff water is a silt fence. These are temporary devices, used primarily on construction sites. The fence is porous fabric held up by wooden or metal stakes. Runoff water moves through the fence material. A single 100-foot run of fence can hold back 50 tons of sediment. The advantages of silt fences are their low cost and simple design. However, they have shown limited effectiveness for sediment control due to poor installation practices, improper placement, and/or inadequate maintenance (USEPA 2012). Training in their placement and enhanced installation methods have reduced some of these challenges (USEPA 2012). However, the silt fence was never designed to remove heavy metals or other contaminants from the sediment and runoff water.

Current methods for treating heavy metals in runoff water, as suggested by the Federal Remediation Technology Roundtable (FRTR), include precipitation and flocculation, treatment with ion exchange resins, and phytoremediation (http://www.frtr.gov, accessed 11 November 2015). The costs of these technologies are driven by size and complexity of the site being treated, pre-treatment requirements, and post-treatment/disposal of contaminated treatment waste. For example, removal of heavy metals by precipitation/flocculation requires collection of the stormwater to be treated, disposal of the contaminated sludge, and a system to return the treated water to the surface water. The precipitation/flocculation treatment is reported to cost from $19.99 to $48.20 per 1,000 gallons of water treated ($2015). This cost includes design and contingency calculations. This cost does not include either the pre- or post-treatment. For example, sludge disposal could add an additional $0.50 per 1,000 gallons. This cost also does not include the construction of a concrete retention pond to collect the runoff water ($205,300 $2015). Ion exchange requires pre-treatment to remove suspended solids from the water being treated and would best be employed as part of a treatment train. The regenerant would also need disposal.

Phytoremediation would require design and construction of a shallow wetland. Metals are removed from the collected sediment and water through ion exchange, absorption, and precipitation with geochemical and microbial oxidation and reduction. Seasonal conditions may limit the effective treatment time and, like the other treatments described above, it requires a large area of land committed to this purpose. Interstate Technology Regulatory Commission (ITRC) (2005) notes

that project management and engineering for wetlands construction projects can run as high as 10% to 20% of the total budget. Other costs, outside the straightforward purchase of land and plants, include permitting, and post-construction monitoring and maintenance. These non-construction costs can run as high as another 25% of the total project cost.

The flexible reactive berm was designed to be a low-cost alternative technology between simple sediment removal devices and complicated and expensive metal treatment technologies. The reactive barrier:

- retains the flexibility and sediment removing function of the silt fence, and
- adds the ability to remove metals directly from runoff water and sediment fines.

The reactive barrier technology quantifies cost by linear foot of barrier instead of gallons of water treated. The model specifies the quantity of barrier required based on the historical average rainfall amounts, historical maximum storm events, and the soil type of the area. There are also alternative amendments for use in the reactive berm that are available commercially, including MetalLoxx® by Filtrexx.

Costs of installation and maintenance of the flexible, reactive barriers for the North and Center Kinder Ranges over a 30-yr operational life span are shown in Table 13. Although a direct comparison to water treatment costs are not possible, the 30-yr total cost of the reactive barriers is much less than a stormwater detention pond plus flocculation, ion exchange, and hazardous waste disposal of contaminated sediment.

Table 9. Cost per Linear Foot for Removing Metals from Runoff Water ($2015) Using Reactive Filter Barriers for a 30-yr Operational Timeframe.

Item	Cost	North Kinder Range	Center Kinder Range
Linear feet required for initial installation		20	180
Cost per foot of pre-filled reactive barrier (cost range depends on selected amendment)	$3.33 to 14.58	$67 - $292	$599 – $2,624
Shipping per foot	$2.08	$42	$374
Total material cost		$109 - $334	$973 - $2,998
Labor for installation	$1,000 for 2 ranges	$500	$500
Total for initial installation		**$609 - $834**	**$1,473 – $3,498**
Number of overhauls		1 per 4 years, (10 ft)	2 per year, (120 ft)
Cost for maintenance (filter barrier + shipping + labor))		$554 to $667	$1,150 to $2,500
Number of overhauls in 30 yr		7.5	30
Total cost of overhauls for 30 yr		**$4,155 to $5,003**	**$34,500 to $75,000**
30 yr Total Cost (Initial + Overhaul)		**$4,764 to $5,837**	**$35,973 to $77,500**

A large amount of contaminated sediment was removed from the Kinder Range runoff water from both the North and Center Ranges (Table 10). Cost avoidance calculations used the volume of sediment and the concentration of Pb in the sediment compared to the cost of remediation of that sediment. The Lowest Effect Level (LEL) for Pb in sediment has been set at 31 mg/kg. This is the concentration at which sediments are considered marginally polluted. Ecotoxic effects become apparent in these sediments but the majority of sediment-dwelling organisms are unaffected. In contrast, the Severe Effect Level (SEL), set at 250 mg/kg Pb, is the point at which the health of sediment-dwelling organisms is affected.

Table 10. Cost Avoidance of the Flexible Reactive Filter Barriers Based on Ecotoxic Screening Levels of Pb in Sediment.

Range	Average [Pb] (mg/kg)	Sediment Volume (yd^3)	Total Sediment Volume at SEL	Remediation Cost[1] ($K)	Total Sediment Volume at LEL	Remediation cost[1] ($K)
North	4,400	2	35	17.6	284	142
Center	5,967	16	282	190.9	3,080	1,540

[1]Remediation cost estimated at $500/yd^3

8.0 IMPLEMENTATION ISSUES

No potential regulations apply to the use of this technology. End-user concerns were to reduce the amount of lead reaching the river in solution and sorbed to sediment carried by stormwater runoff crossing the SAFRs. This was accomplished. The reactive barrier filter sock used in the demonstration employed the TRAPPS™ amendment to adsorb heavy metals from solution and bound to sediment fines. There are additional metal-sorbing amendments and filter socks commercially available. This field demonstration verified the usefulness and cost effectiveness of this approach.

Implementation issues and recommendations associated with the reactive filter barriers were detailed in the project final report. In summary, implementation issues were minimal on the North Kinder Range. The North Range was modeled for barrier sock number and placement prior to deployment. The relatively level drainage area provided gentle water flow without major sediment release from the hillside berm. The sediment in the stormwater runoff was contained by the sock filters.

The contractor-recommended long-term maintenance solution for the North Kinder Range is to place two, 10 foot long reactive filter barriers three feet apart at the base of the berm hill. With the small amount of sediment flowing in this area, these socks would last up to four years before replacement was needed. The majority of the sediment-bound metals and metal(loids) would be removed from the storm water at this point. Planning should include removal and replacement of the leading filter on the slope at least every four years and the second filter every eight years. With no sediment flow to cause issues, the storm water could be filtered again on the north side drainage area using two reactive filter barriers to adsorb any remaining heavy metals and metal(loid)s in solution.

The reactive barriers are contaminated with heavy metals. A TCLP test would determine whether hazardous or non-hazardous waste disposal would be required. Any sediment collected upstream of the barriers would require hazardous waste disposal.

In contrast, the Center Kinder Range was not modeled prior to deployment of the filter barriers. The Center Range received significant high velocity stormwater runoff with a high sediment load which resulted in filter sock clogging and sediment buildup. The sediment also bound high concentrations of lead.

The contractor-recommended long-term maintenance solution using reactive barriers would employ approximately 60 feet of reactive barrier in a line approximately 9 to 12 feet back from the rear of the target trough, with an additional 60 feet approximately six feet behind the first. Another 60 feet of reactive filter barrier should be placed immediately behind the cement target trough. For maintenance of the center range, the layer closest to the hill berm (Sock 1) would be replaced every year. Sock 2 would be replaced every other year. Sock 3 would be replaced every third year. In the case of the Center Range, implementation of reactive filter barriers may require some preliminary site engineering to reduce water velocity and sediment load.

In summary,

- Reactive filter barriers were successful at removing sediment from runoff water when placed according to the stormwater model developed by ERDC-EL.
- Reactive filter barriers were successful at removing Pb from runoff water when placed according to the stormwater model developed by ERDC-EL.
- Coarse sand would provide greater flow through the reactive filter barriers and decrease sediment deposits upstream of the barriers.
- Heavy metal adsorption amendments in the reactive filter barrier allow the barrier contents to pass the TCLP which reduces hazardous waste disposal costs.

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